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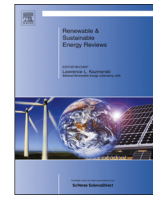

Carbon footprint estimation of Chinese economic sectors based on a three-tier model

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ABSTRACT

To respond to the call of greenhouse gas emissions mitigation, an efficient carbon accounting framework should be proposed. Traditional narrowly defined estimation protocols that consider the direct emissions from native energy consumption may generally lead to underestimates of the carbon emissions derived from providing products and services. To comprehensively evaluate the supply-chain carbon performance in all economic sectors of China, the Economic Input–Output Life Cycle Assessment (EIO-LCA) based carbon footprint accounting framework should be employed. Because carbon emissions also occur in non-energy production processes, carbon emissions from the non-energy industrial process should also be incorporated into the accounting framework. This paper assessed 3 scopes of carbon emissions of Chinese economic sectors, including (1) direct emissions from energy consumption, and the industrial process, (2) emissions from purchased energy, (3) supply chain emissions combining both fuel combustion and industrial processes. The results shown that there is a huge underestimation of the carbon emission from various sectors using traditional carbon protocols compared with the tier 3 supply-chain CO_2 emission. The emissions from industrial processes also constitute a large proportion, which cannot be ignored. In addition, we find that embodied CO_2 emissions in exports concentrated on primary energy intensive sectors, indicating the importance of restructuring of export goods and services. It is proved that the three tier model provides a tool for decision makers to identify the national high carbon emission sectors and make effective carbon mitigation strategies.

Contents

1. Introduction

In the past decades, China's economy has developed rapidly at the expenses of extensive energy consumption, and high greenhouse gas emissions. Consequently, CO_2 emissions increased

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dramatically from 3659.3 million tons to 8332.5 million tons from 2000 to 2010. Since 2006, China has become the largest CO_2 emitter in the world [1]. To respond to the call of the international community to control greenhouse gas emissions, the Chinese government made a commitment before the 2009 U.N. Climate Change Conference in Copenhagen that, by 2020, China's CO_2 emission intensity intends to drop 40–45% compared with the emissions in 2005. To guarantee the realization of this goal, the current carbon emission status in China should be identified.

When considering greenhouse gas emissions, carbon inventory analysis is now a prevalent accounting framework, supporting that the producer is responsible for the CO_2 emissions from the production of energy, goods and services. This view can refer to the production accounting principle [2, 3]. From this point of view, CO_2 emissions are all located with the processes actually emitting CO_2 to the atmosphere. The existing CO_2 emission accounting frameworks, such as the World Resources Institute [4], the Local Government Operation Protocol [5] and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [6] are all based on this production accounting principle. These protocols provide detailed and unified carbon emission accounting guidance incorporating different carbon sources and sinks. However, inventory analysis only considers direct emissions from native energy consumption and the generation of purchased electricity. The specific complexities of the national economy, which is characterized by complex and multiple supply chains and sector interactions, are not addressed, and little attention is given to tracking back to the indirect emissions out of the system boundary. Following narrowly defined estimation protocols will generally lead to underestimates of the carbon emissions that are derived from providing products and services.

Thus, expanding the carbon accounting scale is expected to exactly estimate the lifetime carbon emissions of a sector. The term “carbon footprint” originated from the ecological footprint emerged and provides a guideline to scale up the carbon accounting framework. Although a range of definitions on “carbon footprint” exists [7–9], there is still not a universal accepted one. In this paper, “carbon footprint” is used to investigate the carbon emission embedded in both direct and indirect activities in a specific economic sector. As Wiedmann and Minx have defined: the carbon footprint is a measure of the exclusive total amount of CO_2 emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product [10], it is not a spatial indicator, measured in hectare or square meter, but accumulative CO_2 emissions measured in tons.

The economic input–output model that was first proposed by Leontief [11] facilitates a deeper appreciation of the consumer accounting framework, based on which one method to trace the carbon footprint of national economies is proposed and widely applied, i.e., Economic Input–Output Life Cycle Assessment (EIO-LCA) [12–14]. This approach combines life cycle analysis with input–output analysis and investigates the relationship between economic activities and the energy–environment relationship [15,16]. The application of EIO-LCA technique allows us to trace the direct and indirect energy-related CO_2 emissions associated with a product or service, i.e., the carbon footprint [17]. It is therefore a main frontier method for benchmarking indirect carbon emissions from intermediate consumptions in recent research [18–24].

As national carbon footprints can help design equitable and efficient climate agreements that avoid shifting problems to other administrative territories [25], there is a growing number of studies on the input–output analysis based carbon footprint accounting of nations, e.g., China [18,26,27], Sweden [28], Australia [29], the U.S. [30], Turkey [31]. In order to understand the key drivers behind China's growing energy consumption and the associated CO_2 emissions, which is critical for the development of global climate policies and provides insight into how other emerging economies may develop a low emissions future, Peters et al. analyzed how changes in China's technology, economic structure, urbanization, and lifestyles affect CO_2 emissions using Chinese economic input – output data and structural decomposition analysis [32]. Minx et al. provided more detailed decompositions to account for a larger variety of drivers of China's carbon emission, such as process emissions, energy mix, urbanization, etc [33]. To identify the significance of the supply chain CO_2 emissions that should be included in carbon footprint guidelines, Matthews et al. proposed different scopes for carbon footprint accounting frameworks, including direct emissions, emissions from purchased energy and supply chain emissions. This three-tier carbon footprint estimation model thereby proved to be robust in tracking the total emissions across the entire supply chain [34]. Following this work, Huang et al. employed this model to identify the upstream emission sources that are likely to contribute significantly to the footprints of different sectors in the U.S [35]. The three-tier model is found to be useful in estimating both direct and embodied carbon emissions and could be used as a tool for policy makers to allocate carbon emissions among different sectors.

In some instances, industrial process emissions are produced in combination with fuel combustion. In China, the CO_2 emission that occurs in the industrial process is also a pronounced carbon source, which constitutes 9% of the total emissions [36]. However, few of the available literature, to our knowledge, has so far provided an in-depth understanding of the role of industrial process emissions in national carbon footprint accounting. Coupled with the EIO-LCA model, the industrial process CO_2 emission embodied in products of a sector can be categorized according to different downstream consumers. To portray the influence of industrial technology on the carbon footprint of different sectors, in this paper, we thereby decompose the three tier model to elaborate the role of energy consumption and industrial process carbon emissions.

The goal of this work is to categorize the upstream emission sources to identify the significant categories (industry or sector) that should be emphasized in a national CO_2 emission accounting framework. We extend our earlier analysis by (1) providing specific analysis of carbon footprint analysis of China in three scopes, i.e., production emissions (production and exports), emissions from purchased energy consumption (e.g., electricity); and consumer perspective carbon emissions (consumption and imports); (2) providing more detailed decompositions to account for energy related emission and process emissions. This is, to answer the questions that “is CO_2 emission caused by direct energy consumption on behalf of total carbon emission of each sector?”, “Are carbon emissions of some sectors underestimated according to the current accounting framework?”. The rest of the paper is organized as follows. In the methodology section, the three-tier model is reviewed. In Section 3, this model was applied to account for the CO_2 emissions of economic sectors in China from different tiers. Finally, some policy implications for carbon mitigation in China are proposed in Section 4.

2. Methodology

2.1. Model

According to the three-tier model proposed by Matthews et al. [34], the direct emissions, the emissions from purchased energy and the supply chain emissions should be accounted and analyzed. To

shed light on specific carbon management, the carbon hotspots in each scope should be further identified. We thereby decompose the accounting framework to consider both energy related carbon emission and industrial process emissions. In China, cement production is one of the largest carbon emission sources. Carbon emissions in cement production industry grew rapidly in recent years, propelled by increasing urbanization rate and expanding construction areas, which demands for large amounts of cement production. It is estimated that the CO_2 emitted from the cement industry is approximately 1200 million tons in 2008 [37]. Because cement production is the largest non-energy CO_2 emission sources, the non-energy CO_2 emissions from this sector are specified to represent emissions from industrial processes in this paper. The accounting framework is then demonstrated as follows (also as shown in Fig. 1):

Tier 1: includes direct emissions from final energy combustion in each sector, i.e., emissions from coal, oil and natural gas, and CO_2 emissions from industrial processes along with production in each sector. This tier is similar to the "producer perspective" [3] used for emissions inventories of countries, states, and so on.
Tier 2: includes emissions embodied in electricity and steam purchased for a sector.
Tier 3: analyzes the energy related embodied CO_2 emissions from the total supply chain, i.e., cradle-to-gate emissions (carbon footprint). In this tier, the CO_2 emissions from industrial processes (i.e., cement production) that allocated to different sectors due to downstream consumption are also accounted based on the EIO-LCA model.

2.1.1. Tier 1 model

Tier 1 emissions are the direct production emissions of a specific sector. Considering the CO_2 emissions embodied in international trade, tier 1 production emission should be calculated by domestic emissions subtract emissions for exports. The calculation of production emissions is specified in Eqs. (1)–(2):

$$E_p = F_e \times E^d + F_i \times P \tag{1}$$

$$E_1 = E_P - E_{\text{exp}} \tag{2}$$

where E_1 is the tier 1 emission, It is a 1×29 matrix. E_p is the CO_2 emission from domestic production, which is a 29-dimensional vector specifying CO_2 emissions from 29 production sectors (The classification of 29 sectors is demonstrated in Table 1.). E^d is a 3×29 matrix specifying the use of 3 energy types in 29 sectors, including coal, oil and natural gas. F_e is a 1×3 matrix composed of the CO_2 emission coefficients of 3 energy sources. F_i is the CO_2 emissions from industrial processes per unit GDP for each production sector. In this study, only industrial process emissions from cement production are accounted due to data availability. P is the 29×1 vector, which represents the output value of 29 sectors in China. E_{exp} is the emissions embodied in the exports.

The CO_2 emission factors of the primary energy are based on the CO_2 content of the fuels and the types of energy. The emission factors of fossil fuels such as coal, oil and natural gas are designated as 90.9, 72.93 and 51.19 according to IPCC [6]. For renewable energy, the CO_2 emissions factors are considered to be zero. The non-energy process emission factor of cement production is 0.38 tCO_2/t [38] in China.

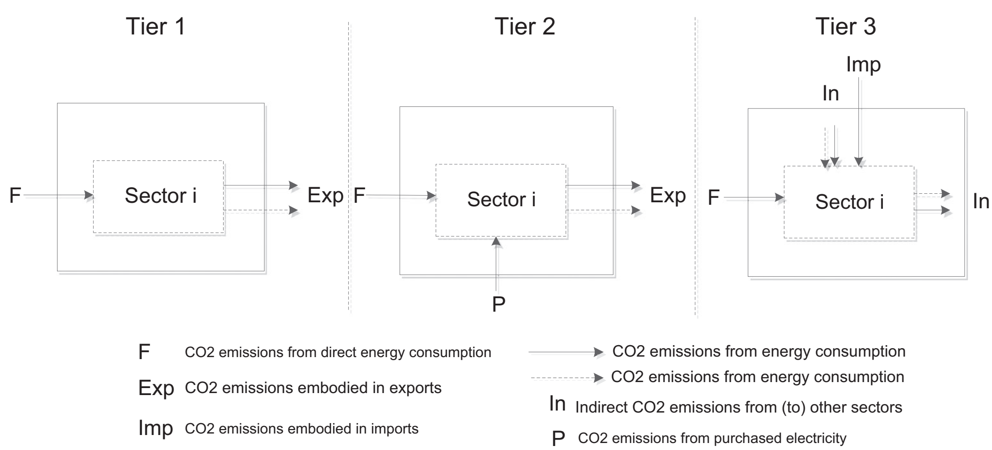

Fig. 1. Three tiers CO_2 flows for a typical sector in a national economy.

Table 1
Sector classification of China.

No.	Sector	No.	Sector
1	Farming, forestry, animal husbandry and fishery	15	Metal products
2	Coal mining and dressing	16	Ordinary and special equipment
3	Petroleum and natural gas extraction	17	Transportation equipment
4	Metals minerals mining and dressing	18	Electric equipment and machinery
5	Nonmetal minerals mining and dressing and other mining and dressing	19	Communication equipment, computers and other electronic equipment
6	Food production and tobacco processing	20	Instruments, meters, cultural and office machinery
7	Textile industry	21	Manufacture of artwork and other manufacturing
8	Manufacture of garment, leather, fur, feather and related products	22	Recycling and disposal of waste
9	Timber processing and furniture manufacturing	23	Electricity, steam production and supply
10	Paper making, printing and cultural educational and sports goods manufacturing	24	Gas production and supply
11	Petroleum, coking and nuclear fuel processing	25	Water production and supply
12	Chemical industry	26	Construction
13	Nonmetal mineral products	27	Transportation, storage, postal and telecommunication services
14	Smelting and pressing of metals	28	Wholesale and retail trades, hotels and catering services
		29	Others

2.1.2. Tier 2 model

The tier 2 emissions incorporate the emissions embodied in the purchased electricity. Although these emissions are not generated onsite, they should be accounted where the electricity is consumed in a consumer perspective. The estimation of the tier 2 emissions is shown in Eq. (3):

$$E_2 = F' \times E^f + F_i \times P \tag{3}$$

where E_2 is a 29 vector, which represents the tier 2 CO_2 emissions from 29 production sectors. It is a 1×29 matrix. E^f specifies consumption of purchased energy sources. F' is the CO_2 emission coefficient of electricity.

Using the "actual energy consumption" principle proposed by Munksgaard and Pedersen [3], all emissions caused by electricity production are specified for each of the fuel inputs (e.g., coal, natural gas and fuel oil), which are used for generating the electricity, while zero emissions are connected to the final use of the electricity and district heating. The total purchased electricity from other countries is 4.25E+09 kWh in 2007. As electricity is imported from Russia and the North Korea, the CO_2 emission intensity of purchased electricity from Russia (341 g CO_2/kWh) [39] is employed for the calculated of CO_2 emissions from purchased electricity. The CO_2 emissions from purchased electricity are then allocated to different sectors based on the electricity consumption structure in China in 2007.

2.1.3. Tier 3 model

The calculation of the tier 3 emissions is based on the input–output table, which was developed by Leontief in the 1930s. An input–output table shows monetary interactions or exchanges between the economic sectors and therefore their interdependence. The rows of an input–output table describe the distribution of a sector's output throughout the economy while the columns describe the inputs required by a particular sector to produce its output [40]. The basic input–output model derives the total economic purchases (i.e., supply chain) across an economy required to make a vector of desired output, commonly called the "final demand" [34], as shown in Eq. (4). By multiplying the required inputs X with the energy consumption vector E^d and the CO_2 emission coefficient matrix F_i, the direct and indirect emissions generated from energy consumption in the domestic supply chain are calculated and shown in Eq. (5):

$$X = (I + A + A \times A + A \times A\ldots..)Y = (I - A)^{-1} Y \tag{4}$$

$$E_e = F_i \times E^d \times X = F_i \times E^d \times (I - A)^{-1} Y \tag{5}$$

Where X portrays the required inputs of a specific sector. E_e is a 1×29 matrix, signifying the supply chain CO_2 emissions from energy consumption in 29 production sectors. A is a matrix of intermediate consumption where the columns represent the input from each industry (domestic plus imports) to produce one unit of output for each domestic industry. $(I-A)^{-1}$ is the 29×29 Leontief inverse coefficient matrix. Y is the 29×1 vector, which represents the final demands of 29 sectors in China.

Considering the non-energy industrial process emissions, the total emissions E_c in a consumer perspective are calculated by Eq. (6).

$$E_c = F_i \times E^d (I - A)^{-1} Y + E^i (I - A)^{-1} Y \tag{6}$$

where E_c is the sum of CO_2 emissions from both energy consumption and industrial process. E^i is the 1×29 matrix specifying the CO_2 emissions from industrial processes per unit GDP for 29 production sectors. In this paper, only the non-energy industrial process CO_2 emissions of the Nonmetal Mineral Products sector (cement production) are considered due to data availability.

Many critiques suggest the use of consumption-based inventories which subtract exports but include imports [3,41–46]. To calculate the carbon footprint in a national scale, the CO_2 emissions from imports should thus be included. There are two main approaches that exist to determine the environmental impacts of imported goods and services [47]. One considers total bilateral trade between regions (EEBT) and the other considers trade to final consumption and endogenously determines trade to intermediate consumption (MRIO). As the EEBT model is more relevant for considering the environmental impacts of aggregated imports to a country, it is applied in this study to calculate the CO_2 emission embodied in imports to China. Considering energy consumption related CO_2 emissions, emissions from industrial processes, and CO_2 emissions embodied in imports, the tier 3 emission is specified as Eq. (7):

$$E_3 = E_c + \sum_r f^r (I - A^r)^{-1} e^{rs} \tag{7}$$

where E_3 is the tier 3 emission. f^r is a row vector with each element representing the CO_2 emissions per unit industry output in country r. A^r represents the intermediate consumption matrix of country r. e^{rs} is the imports from country r to China (s).

2.2. Data sources

The calculation of the carbon footprint of each sector is established based on the input–output table for China for the year 2007 [48]. The energy consumption data are selected from the China Energy Statistical Yearbook 2010 [49]. Because the economic input–output tables encompass 42 sectors while the China Energy Statistical Yearbook classified economic activities into 44 sectors, we aggregate all of the economic sectors and reclassify them into 29 industry groups to ensure consistency in sector classification, as shown in Table 1.

The energy intensity, which is specified as the energy consumption per economic income, is employed to demonstrate the energy cost along with economic development. It also functions as a goal-function for tradeoffs between energy savings and economic development. In this paper, the energy intensity is calculated by dividing the tier 3 emissions by the economic outputs of specific sectors.

3. Results

3.1. Tier 1 CO_2 emissions

The total direct CO_2 emissions from energy consumption (E_p) amount to 8.58 E+09 t. As shown in Fig. 2, the largest direct emitter is Sector 23 (electric power/steam and hot water production and supply), which contributes 34.46% (2.96 E+09 t) to the total CO_2 emissions. The large amount of CO_2 emission from electricity generation is induced by the growing electricity demand in China. With an average growth rate of 11%, the total electricity consumption reached 4190 billion kWh in 2010. In the report "The twelfth five-year plan of electricity industry" announced by China Federation of Electric Power Enterprises, electricity consumption will amount to 5990–6570 kWh in 2015 with an annual growth rate of 8.5% [50]. Therefore, how to minimize CO_2 emissions from electricity industry remains an important topic in China. Due to a large quantity of crude oil consumption, Sector 11 (the petroleum, coking and nuclear fuel processing) is the second contributor of tier 1 emissions in China (1.52 E+09 t, 17.77% of the total E_p). Sector 14 (smelting and pressing of metals) is the third CO_2 emission source, which constitutes 15.83% of total emissions. In addition, non-energy

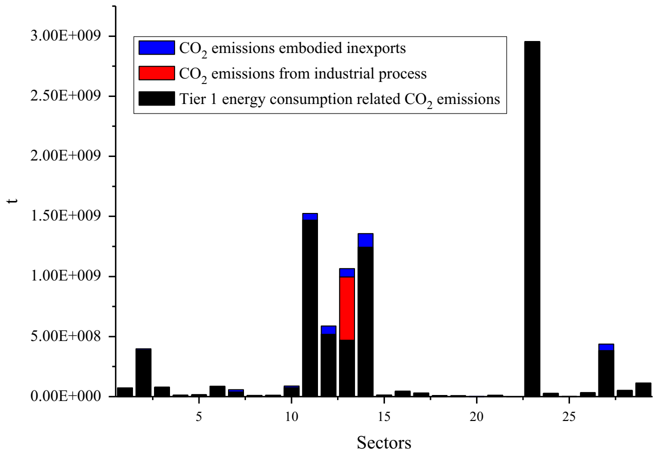

Fig. 2. The CO_2 emissions from Tier 1.

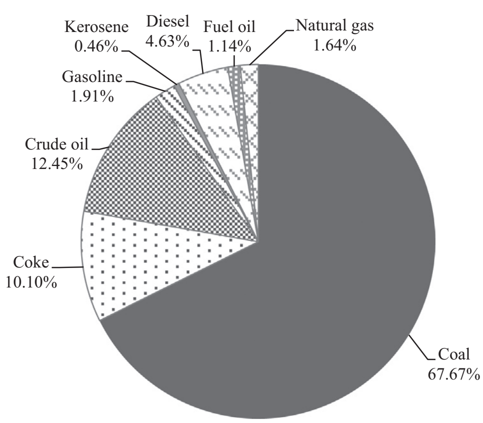

Fig. 3. The proportions of CO_2 emissions from different energy sources.

industrial process emission is another carbon source that cannot be ignored. As shown in Fig. 2, taken cement production as an example, the emissions from non-energy industrial processes constitute 49.52% of total emissions in "Nonmetal Mineral Products" sector.

Fig. 2 shows the embodied emissions in exports on a sectoral basis. Emissions for exports that generated from industrial activities in China while consumed by other countries should be subtracted from tier 1 emissions. In China, the most carbon-export sector is sector 14 (smelting and pressing of metals), accounting for 25.19% of the total emissions in exports, followed by sector 13 (nonmetal mineral products, 15.07%), and the chemical industry (sector 12, 15.07%). We find that the exports concentrated on primary energy intensive sectors. Transforming the current export structure from energy intensive sectors to high-tech manufactory industries (e.g., Communication Equipment, Computers and Other Electronic Equipment) is a way to alleviate CO_2 emissions in exports.

Fig. 3 demonstrates the structure of energy consumption that used to generate CO_2 emissions in China. Obviously, CO_2 emissions from coal combustion are the largest proportion at 68%, followed by crude oil and coke, which constitute 12% and 10% of the total emissions. Natural gas related CO_2 emissions only compose 1.64% of the total CO_2 emission. Obviously, coal is still the largest contributor of CO_2 emissions in China. Therefore, adjusting the energy structure and expanding the utilization of natural gas and renewable energy are promising ways to respond to the appeal for developing a "Low carbon economy" proposed by the Chinese government.

3.2. Tier 2 CO_2 emissions

Because China is self-sufficient in electricity generation and scarcely any electricity is imported from other countries, there is little CO_2 emission from purchased electricity. It is estimated that CO_2 emissions from purchased electricity are 1.44 E+06 t in 2007, which is less than 1% compared with the tier 1 emissions. By calculating different tier emissions, we find that the first 2 tiers, which are emphasized in "producer-side" accounting frameworks, include only a small fraction of the total supply chain (tier 3) footprint for most industries (Fig. 4). For the average sector, only 13.71% of the tier 3 (total) GHG emissions are captured by tiers 1 and 2. 75.86% of all economic sectors providing goods and services (22 of the 29 industries) have less than 20% of their total carbon footprint represented by tiers 1 and 2. Sectors that would have most of their footprint represented by tiers 1 and 2 are respectively Coal Mining and Dressing (sector 2, 50.42%), Petroleum, Coking and Nuclear Fuel Processing (sector 11, 60.46%), and Electricity, Steam Production and Supply (sector 23, 52.53%), which are energy production sectors. Because carbon emissions are concentrated on direct fossil fuel combustion in these sectors, the tier 3 carbon footprint can be mostly captured by the tier 1 boundary.

3.3. Tier 3 CO_2 emissions

As defined in Eqs. (5)–(7), tier 3 emissions include three parts, i.e., supply-chain CO_2 emissions from energy consumption, CO_2 emissions from non-energy industrial processes, and emissions embodied in imports to China. Fig. 5 demonstrates the total tier 3 CO_2 emission of different sectors. For supply-chain CO_2 emissions from energy consumption, the top-4 sectors are electricity, steam production and supply (sector 23), smelting and pressing of metals (sector 14), the chemical industry (sector 12), and the construction industry (sector 26) in 2007. The electricity, steam production and supply sector is a well-known source of CO_2 emissions for the direct emissions from burning fossil fuels, with 52.74% of their total emissions in tier 1. The smelting and pressing of metals sector is a sector with low tier 1 and tier 2 emissions relative to its total footprint and is involved with substantial manufacturing for raw material inputs such as metals and non-metals, which fall outside of traditional tier 1 and tier 2 footprint approaches and are industries with great fossil fuel consumptions. The chemical industry and the construction industry are also sectors with large underestimations in tiers 1 and 2, implying that the embodied CO_2 emissions in input raw metallic minerals is

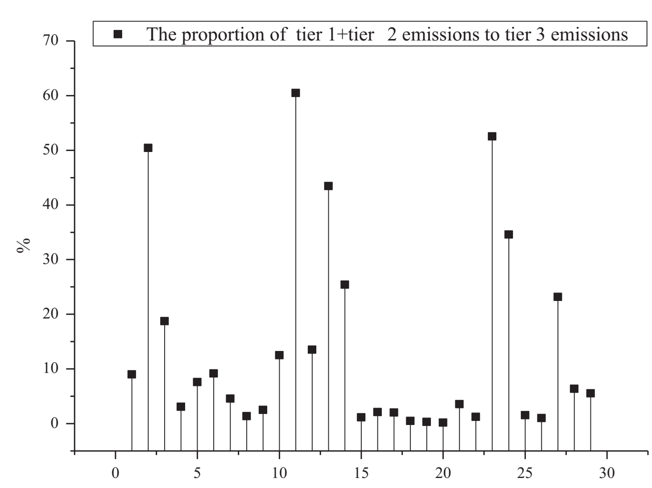

Fig. 4. The proportions of Tier 1 and Tier 2 carbon emissions in Tier 3.

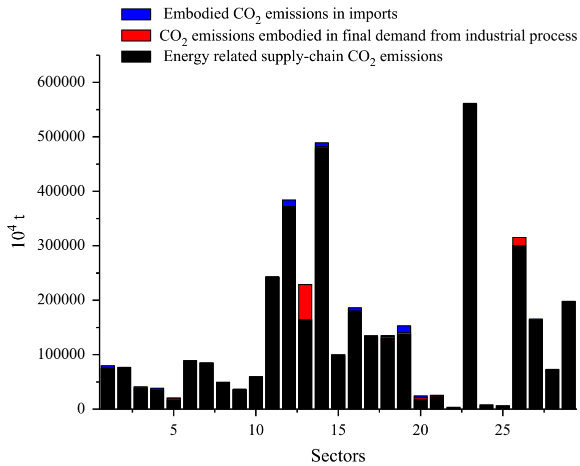

Fig. 5. CO_2 emissions of different sectors in Tier 3.

relatively high. From a life-time consumer perspective, because energy is delivered and consumed by other sectors, the energy production sectors, i.e., coal mining and dressing (sector 11), gas production and supply (sector 24), and water production and supply (sector 25), have less responsibility for total carbon emissions.

The average CO_2 emission of the tertiary industry is 1.44 E+09 t, which is even larger than the secondary industry (1.33 E+09 t). Obviously, although the tertiary industry does not directly discharge CO_2 emission, the CO_2 emissions embedded in materials that are delivered to serve the tertiary industry contribute significantly to sector-level carbon emissions. Therefore, the promotion of energy-savings and low-carbon material utilization in the tertiary industry can serve the purpose of systematic carbon reduction by focusing on the supply chain carbon management.

CO_2 emissions are not generated merely from fossil fuel combustion but also indirectly from the industrial production processes, i.e., industrial processes that chemically or physically transform materials (for example, the cement industry are notable examples of industrial processes that release a significant amount of CO_2 from calcium carbonate decomposition) [6]. In this paper, due to the lack of data, only the emissions from cement production are calculated. As shown in Fig. 5, for the average sector, 4.77% of the tier 3 (total) GHG emissions are captured by non-energy industrial processes, which indicate that incorporating CO_2 emissions from industrial processes into carbon footprint accounting is an indispensable part of carbon accounting. Among the sectors, the indirect carbon emissions from non-energy industrial processes account for a considerable portion in sector 5 (nonmetal minerals mining and dressing and other mining and dressing), 13 (nonmetal mineral products), and 20 (instruments, meters, cultural and office machinery). Specifically, due to the substantial utilization of cement as raw materials, the CO_2 emissions from industrial processes are concentrated in the nonmetal mineral products sector, instruments, meters, cultural and office machinery sector, and the construction sector, which constitute 53.43%, 3.30%, and 12.24% of total industrial process CO_2 emissions, respectively.

As imported goods and services are consumed in China, CO_2 emissions embodied in imports should also be accounted as a part of carbon footprint in a consumer perspective. According to statistics of imports [51], the largest 10 importers for China are respectively Japan, EU, ASEAN (the Association of Southeast Asian Nations), Korea, Taiwan, U.S., Australia, Russia, Saudi Arabia, Brazil, and other countries. Table 2 lists the proportion of imports from these countries to China.

Table 2
The top 10 importers of China.

Countries	Proportions (%)	Countries	Proportions (%)
Japan	14	U.S.	7.3
EU	11.6	Australia	2.7
ASEAN	11.3	Russia	2.1
Korea	10.9	Saudi Arabia	1.8
Taiwan	10.6	Brazil	1.9
Other countries	25.8		

When the EEBT approach is used to calculate the embodied CO_2 emissions in imports, the sectoral CO_2 emission intensities of these importers should be identified. According to Chen [52], CO_2 emission intensities of different sectors in all these importers are listed in Table 3. In this study, we choose the smallest CO_2 emission intensity (gray cells in Table 3) among the importers in each sector to characterize the CO_2 emissions embodied in imports, which benchmark a floor level of CO_2 emissions in imports to China.

As shown in Fig. 5, the embodied CO_2 emissions in imported goods also constitute a significant part of total carbon footprint. For a sectoral average, the fraction of CO_2 emissions in imported goods in total tier 3 carbon footprint is at least 3.39%. Among all economic sectors, the leading emissions sources in imports are Sectors 19 (electronic and telecommunications equipment), 12 (chemical industry) and 14 (smelting and pressing of ferrous and nonferrous metals), respectively, which should be paid more attention in international trading management. Sector 19 (communication equipment, computers and other electronic equipment) has the largest volume (1.26 E+08 t, 18.59% of total), followed by Sectors 12 (chemical industry, 1.17 E+08 t, 17.22% of total) and 14 (smelting and pressing of metals, 7.32 E+07 t, 10.79% of total). In addition, Sectors 1 (farming, forestry, animal husbandry and fishery), 4 (metals minerals mining and dressing) and 16 (ordinary and special equipment) also account for considerable imported emissions (6.78%, 5.30% and 8.49%, respectively). By decomposing the industrial structure, we find that primary, secondary and tertiary industries contribute 6.78%, 88.00% and 5.22% to the total embodied CO_2 emissions in imports, respectively.

Fig. 6 demonstrates the tier 3 CO_2 emission intensity of China. Sector 23 (electricity, steam production and supply) has the largest CO_2 emission intensity of 1.1 E−02 t/$, followed by Sectors 11 (petroleum, coking and nuclear fuel processing) and 13 (nonmetal mineral products) with intensities of 7.14 E−03, and 6.23 E−03 t/$, respectively. These sectors all belong to energy intensive sectors and should be regarded with an emphasis on energy reduction and control. The average intensity of secondary industries (3.57 E−03 t/$) is 3.52 times larger than that of primary industries (1.01 E−03 t/$) and 2.06 times larger than that of tertiary industries (1.73 E−03 t/$).

4. Discussions

At the sector level, although the energy intensities of the energy production sectors are relatively high, the energy products of these sectors perform as the basic inputs to fuel the development of other sectors. From a supply-chain perspective, only a small part of the embodied CO_2 emissions are captured by these sectors. To this end, in addition to directly increasing the energy efficiency in energy intensive sectors, minimizing material inputs and shortening unnecessary supply chains to sector-level production are also efficient ways to reduce indirect emissions. This point is specifically important for sectors with long supply chains.

More effort is suggested to eliminate or reduce production from inefficient and carbon-intensive industrial sectors, technologies and facilities, such as electricity, steam production and supply

Table 3
CO_2 emissions intensities of different sectors of the top 10 importers (Unit: tCO_2/million dollars).

	Japan	U.S.	EU	Korea	Taiwan	ASEAN	Australia	Russia	Saudi Arabia	Brazil
1	1225.36	2726.64	4223.66	2104.14	8195.36	4859.64	2882.86	4155.43	3383.79	7437.71
2	16199.00	1947.00	6093.22	7929.00	80405.00	5632.80	2133.00	6557.00	1261.00	9684.00
3	314.00	991.50	108084.69	780.00	3294.00	2769.20	1181.00	1627.00	1045.50	1010.50
4	677.00	989.00	1195.70	547.00	706.00	1791.00	1012.00	997.00	1288.00	1107.00
5	677.00	989.00	1195.70	547.00	706.00	1791.00	1012.00	997.00	1288.00	1107.00
6	793.38	1481.63	1428.35	1678.25	1528.38	3313.65	1882.63	3800.13	3010.75	5407.75
7	698.00	824.00	700.04	1404.00	1291.00	1406.40	781.00	2956.00	1181.00	972.00
8	594.50	849.00	569.89	1178.00	1267.00	1218.90	1014.00	1985.00	1174.50	1545.50
9	352.00	591.00	607.07	916.00	606.00	696.60	595.00	6442.00	1049.00	541.00
10	458.00	874.00	695.85	1044.00	987.00	1531.40	618.00	1527.00	2257.00	800.00
11	1124.00	1852.00	1443.63	633.00	906.00	2067.20	1261.00	3100.00	3808.00	968.00
12	796.00	1196.00	1270.11	1337.00	1552.00	1469.40	959.00	5345.00	3949.00	1343.00
13	795.00	1549.00	1609.04	2048.00	2634.00	4325.40	1551.00	4946.00	2577.00	1546.00
14	1050.50	1653.00	1695.24	1698.50	1791.00	2524.00	2725.00	4801.50	3669.50	2227.50
15	482.00	761.00	821.81	1037.00	1280.00	1669.40	867.00	3462.00	1945.00	963.00
16	507.00	613.00	594.93	883.00	736.00	1454.60	623.00	1490.00	1259.00	617.00
17	356.00	600.00	547.56	811.00	816.00	852.20	549.00	2002.00	783.00	661.00
18	371.00	529.00	614.85	752.00	967.00	946.60	732.00	3108.00	1375.00	631.00
19	480.00	950.00	667.85	759.00	857.00	1010.40	986.00	6654.00	1564.00	735.00
20	507.00	613.00	594.93	883.00	736.00	1454.60	623.00	1490.00	1259.00	617.00
21	507.00	613.00	594.93	883.00	736.00	1454.60	623.00	1490.00	1259.00	617.00
22	507.00	613.00	594.93	883.00	736.00	1454.60	623.00	1490.00	1259.00	617.00
23	3010.00	9251.00	5389.19	7058.00	11577.00	10357.00	12794.00	17832.00	13300.00	1296.00
24	491.00	1592.00	32993.52	467.00	3126.00	4381.60	5125.00	3057.00	1447.00	2082.00
25	262.00	840.00	910.85	1166.00	960.00	1948.20	544.00	2941.00	2789.00	1342.00
26	307.00	385.00	557.59	684.00	956.00	1377.40	491.00	1858.00	1139.00	396.00
27	1439.25	1936.00	2356.57	5500.25	2776.50	4140.00	1260.75	4176.00	6977.25	3668.50
28	206.00	201.50	654.13	365.50	272.00	512.40	262.50	645.00	1252.50	255.50
29	166.40	343.40	363.55	416.80	302.20	1067.60	268.00	1604.20	873.00	365.80

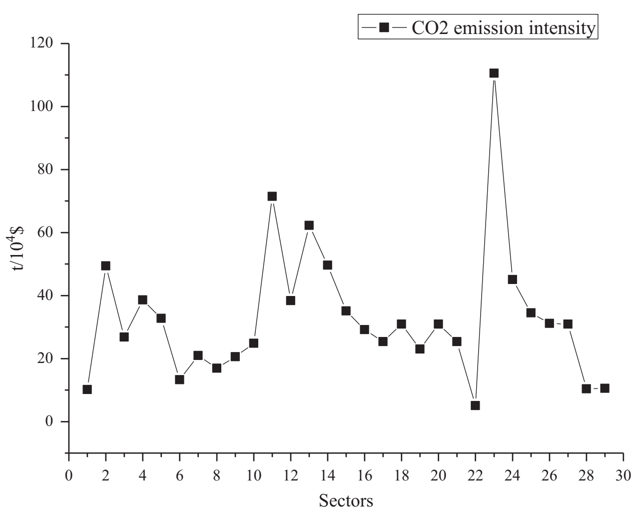

Fig. 6. CO_2 emission intensities of different sectors in China.

(sector 23), smelting and pressing of metals (sector 14), the chemical industry (sector 12), and the construction industry (sector 26), and encourage the high technology industry and service industries, which have a low carbon density, such as the instruments, meters, cultural and office machinery (sector 20), manufacture of artwork and other manufacturing (sector 21), recycling and disposal of waste (sector 22), water production and supply (sector 24), and water production and supply sectors (sector 25), as Fig. 5 shows. This recommendation denotes the transition of the industrial structure away from heavy industry to less energy extensive industries that produce higher value-added products and service industries.

The tertiary industries have pronounced carbon footprint in view of tier 3 supply-chain emissions. However, the CO_2 emission intensity of the tertiary industry is much lower than the secondary industry due to its high economic output. Thus, to achieve the commitment that the CO_2 emission intensity of China would be reduced by 40–45% in 2020 compared with that of 2005, the proportion of the tertiary industry should be further expanded. Meanwhile, it is imperative to practice and promote “energy savings” and the “low carbon” lifestyle in the tertiary industry to reduce demands from other sectors and ultimately realize a CO_2 emission reduction. Energy audit programs are promising measures for regulating energy behaviors in the tertiary industry. In addition, the establishment of low carbon standards for the tertiary industry should be emphasized and accelerated to provide guidelines for the carbon management of enterprises in the tertiary industry.

In this paper, CO_2 emissions from non-energy industrial processes that are often ignored in accounting frameworks are also calculated. It is concluded that the CO_2 emissions from non-energy industrial processes also occupy a large proportion of the total emission. To control the non-energy CO_2 emission derived from industrial processes, the production technologies should be upgraded strictly according to the requirements of the Guiding Catalog of Industrial Structure Adjustment (2011). Specifically, for the cement production sector, the utilization of non-carbonated raw materials should be promoted, such as acetylene sludge, paper sludge, desulfurized gypsum, coal ash and slag.

Quantifying CO_2 emissions associated with trade will shed light on opportunities and priorities for implementing mitigation programs like the Kyoto Protocol and Clean Development Mechanism. We suggest that the export of “clean” manufacturing technologies from China would decrease the current trade imbalance, reduce pollution loading and related negative environment impacts in China, and mitigate net global emissions.

The coal-dominated energy structure is responsible for the majority of the total CO_2 emissions in China. Energy restructuring is thereby advisable for carbon mitigation. To ease the coal-dominated environmental dilemma, the clean utilization of coal by encouraging the application of coalbed methane and natural

gas should be enhanced. In the following years, guided by the goal that “the proportion of non-fossil fuel to total primary energy consumption should reach 11.4% in 2015”, efforts should be made to enlarge renewable energy utilities according to local conditions, i.e., striving to develop wind power, biogas plants, geothermal power, small hydroelectric power plants, straw gasification and solar energy facilities. According to the goals of the 12th Five-Year Plan, the energy consumption structure should be reorganized. The proportion of hydro and nuclear power to primary energy consumption is expected to increase from 7% to 9%. Wind power, solar energy and bioenergy, which constitute only 0.8% of the total energy consumption currently, are planned to reach 2.6%.

From a technology perspective, a technological outline should be compiled to guide the industrial energy savings and the efficiency improvement. Efforts should also be made to attract investments on the R&D of energy-saving and low-carbon industrial equipment and the application of buildings integrated renewables and green building materials. As a supplementation, the cultivation of the technological service system, e.g., energy and carbon emission metering technology, should be stressed. Carbon decarbonization technologies such as carbon capture and storage (CCS) offer the greatest opportunity for carbon dioxide (CO_2) abatement within China's energy intensive industries. The government should support industry carbon capture and storage demonstration in key sectors, increase the carbon capture investments and include industry more comprehensively in the China CCS roadmap. The government could support the CCS project in various forms, including the project construction funding, the key technology research funding and the purchase of carbon emission reductions after these projects are put into production, among other measures.

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